Bound states of singlet quarks at LHC

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Abstract

We discuss the discovery potential of the bound states of singlet quarks at LHC. We find that it is possible to discover bound states of singlet quarks at LHC with singlet quark masses up to 300 Gev for $e_Q = \frac{2}{3}$ and up to 200 Gev for $e_Q = -\frac{1}{3}$.

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The aim of this paper is the discussion of the discovery potential of the bound states of singlet quarks [1]-[14] at LHC. Singlet quarks are color-triplet fermions whose left and right chiral components are both singlets with respect to the $SU(2)$ weak isospin gauge group. They can mix with the ordinary quarks and as a result of the mixing they decay into ordinary quarks. For small mixing $\epsilon \leq O(0.1)$ the lifetime of singlet quark is less than $O(10)$ Mev so singlet quarks can form bound states. Note that as a result of mixing of singlet quarks with ordinary quarks tree level flavor-changing neutral currents are generated. Bounds from flavor changing neutral currents typically restrict the mixing parameter to be smaller than $O(0.1)$. So if singlet quarks exist they have to be rather longlived and have to form bound states. The phenomenology of bound states of new quarks has been discussed in refs. [11, 12]. Recently it has been conjectured [13, 14] that singlet quarks can solve R_b - R_c problem.

In this paper we study a production and decays of 0^{-+} and 1^{--} superheavy quarkonium states. Other superheavy quarkonium states $0^{++}, 1^{++}, 2^{++}$ have much smaller cross sections and they are practically unobservable [11, 12]. The main difference between our paper and refs. [11, 12] is that we use the LHC total energy $\sqrt{s} = 14$ Tev and STEQ2L parton distributions. Besides refs. [11, 12] consider the case of the 4 th generation doublet. Also we calculate the main backgrounds. The cross section for pseudoscalar 0^{-+} quarkonium production by two gluon fusion in pp collisions can be written in terms of gluonic decay width of 0^{-+} and the gluon distribution $g(x, \mu)$ in a proton as [11, 15]

$$\sigma(pp \to gg \to 0^{-+}) =$$

$$\frac{\pi^2 \tau \Gamma(0^{-+} \to gg)}{8M_{0^{-+}}^3} \int_\tau^1 g(x, \mu) g(x^{-1}\tau, \mu) x^{-1} dx \tag{12}$$

with $\tau = \frac{M_{0^{-+}}^2}{s}$. In nonrelativistic model the decay width of pseudoscalar quarkonium into two gluons is given by the formula [1, 14]

$$\Gamma(0^{-+} \to gg) = \frac{8\alpha_s^2(M_{0^{-+}}^2)}{3M_{0^{-+}}^2}|R_S(0)|^2 \tag{1}$$

Here $R_S(0)$ denotes the radial wave function of the S state at $r = 0$. For the Coulomb potential we have $|R_S(0)|^2 = 4(\frac{2}{3}\alpha_s(M_{0^{-+}}^2)M_{0^{-+}})^3$. For other phenomenological potentials

(Cornell potential, Richardson potential, Wisconsin potential) the value of the radial wave function at zero radius is higher [1, 11] so the use of the Coulomb potential gives the lowest cross section of 0^{-+} pseudoscalar quarkonium production. In this paper we shall use the Coulomb potential. The best way to look for the pseudoscalar quarkonium is through its decay into two photons. The reaction $pp \to 0^{-+} \to \gamma\gamma$ is very similar to the famous reaction $pp \to Higgs \to \gamma\gamma$ which is supposed to be the main reaction for the Higgs boson discovery at LHC. The decay width of pseudoscalar quarkonium into two photons is

$$\Gamma(0^{-+} \to \gamma\gamma) = \frac{12\alpha^2 e_Q^4}{M^2}|R_S(0)|^2 \tag{2}$$

Here e_Q is the charge of the singlet quark Q in units of the proton charge. We have calculated the cross sections for the pseudoscalar quarkonium production using the parton distributions STEQ2L of ref.[16]. In our calculations we have used PYTHIA 5.7 and JETSET 7.4 generators [17]. We took the value of the renormalization point μ equal to the mass $M_{0^{-+}}$ of the pseudoscalar quarkonium. We put strong coupling constant $\alpha_s(M_Z^2) = 0.120$, effective electromagnetic coupling constant $\alpha \equiv \alpha(M_Z^2) = \frac{1}{128}$ and top quark mass $m_t = 175$ Gev. We have checked also that the variation of the renormalization point μ in the interval $0.5M_{0^{-+}} - 2M_{0^{-+}}$ leads to the variation of the cross sections less than 30 percent. In our estimates we assumed the integral luminosity $\int L = 10^5 (pb)^{-1}$ and the total energy $\sqrt{s} = 14 Tev$. The main background for the reaction $pp \to 0^{-+} \to \gamma\gamma$ comes from:

1. prompt diphoton production from quark annihilation and gluon fusion diagrams and bremsstrahlung from the outgoing quark line in the QCD Compton diagrams

2. background from jets, where an electromagnetic energy deposit originates from the decay of neutral hadrons in a jet or from 1 jet + 1 prompt photon.

The jet background is reduced [18] by imposing an isolation cut, which also reduces the bremsstrahlung background. The photon is defined an isolated [18] if there is no charged track or electromagnetic shower with a transverse momentum greater than 2.5 Gev within a region $\Delta R \geq 0.3$ around it. It is assumed that the jet background is reduced to an insignificant level (≤ 10 percent) by the combination of isolation and π^0 rejection cuts

[18]. For CMS detector [18] an efficiency of 64 percent was assumed for reconstruction of each photon (i.e. 41 percent per event). We assumed that the accuracy of the restoration of the diphoton invariant mass is 1 percent that is conservative estimate for CMS detector where the photon energy resolution is assumed to be $\Delta E/E = 0.02/E^{0.5} \oplus 0.005 \oplus 0.2/E$ in the barrel and $\Delta E/E = 0.05/E^{0.5} \oplus 0.005 \oplus 0.2/E$ in the endcap, where there is a preshower detector. In our calculations we have used the following cuts for photons:

$$|\eta| \leq 2.5, \quad |p_t| \geq 25 Gev$$

The results of our calculations are presented in table 1. Our main conclusion is that at LHC for integral luminosity $L = 10^5 \ pb^{-1}$ it would be possible to discover the pseudoscalar quarkonium at the 5σ level for $e_q = -\frac{1}{3}$ with singlet quark masses m_Q up to 100 Gev and for $e_Q = \frac{2}{3}$ with singlet quark masses up to 300 Gev.

For the estimate of the vector quarkonium 1^{--} production we use the cross section for the subprocess $gg \rightarrow 1^{--}g$ equal to [11, 12]

$$\sigma(gg \rightarrow 1^{--}g) = \frac{9\pi^2}{8M_{1^{--}}^3(\pi^2 - 9)}\Gamma(1^{--} \rightarrow ggg)I(\frac{S}{M_{1^{--}}^2}), \tag{3}$$

where

$$I(x) = \frac{2}{x^2}\left(\frac{x+1}{x-1} - \frac{2xln(x)}{(x-1)^2}\right) + \frac{2(x-1)}{x(x+1)^2} + \frac{4ln(x)}{(x+1)^3} \tag{4}$$

The decay width of vector quarkonium into 3 gluons is determined by the formula [1, 12]

$$\Gamma(1^{--} \rightarrow ggg) = \frac{40(\pi^2 - 9)\alpha_s^3}{81\pi M_{1^{--}}^3}|R_S(0)|^2 \tag{5}$$

The most promising decay mode for the detection of vector quarkonium is $1^{--} \rightarrow \mu^+\mu^-$ or $1^{--} \rightarrow e^+e^-$. The main background for the process $pp \rightarrow 1^{--} + ... \rightarrow \mu^+\mu^- + ...$ is the Drell-Yan process. We have calculated the corresponding cross sections for singlet quarks with electric charge $E_Q = -\frac{1}{3}$ (analog of d_R-quark) and for singlet quark with electric charge $e_Q = \frac{2}{3}$ (analog of u_R-quark). The results of our calculations are presented in table 2. Our main conclusion is that for $e_Q = -\frac{1}{3}$ it would be possible to discover singlet quarks with the mass up to 200 Gev and for $e_Q = \frac{2}{3}$ it would be possible to discover singlet quarks with the mass up to 250 Gev.

It should be noted that an account of the production of the radial excitations of 0^{-+} and 1^{--} quarkoniums leads to the increase of the signal cross section approximately by 20 percent [11].

To conclude, in this note we have studied the perspectives of the discovery of the bound states of singlet quarks, namely pseudoscalar quarkonium 0^{-+} and vector quarkonium 1^{--} at LHC. The best way to detect such bound states is the measurement of the diphoton and dilepton invariant masses. LHC will be able to discover the superheavy quarkoniums with singlet quark masses up to 300 Gev for $e_Q = \frac{2}{3}$ and and up to 200 Gev for $e_Q = -\frac{1}{3}$.

Table 1. The cross sections and branchings for the process $pp \to 0^{-+} + ... \to \gamma\gamma + ...$

Here:

1. $\sigma \equiv \sigma(pp \to 0^{-+} \to gg) \cdot \Gamma^{-1}(0^{-+} \to gg)$ in $pb \cdot (Mev)^{-1}$.

2. $\sigma_{cut} \equiv \sigma(pp \to 0^{-+} \to gg||\eta_g| \geq 2.5, |p_{tr,g}| \geq 25 Gev) \cdot \Gamma^{-1}(0^{-+} \to gg)$ in $pb \cdot (Mev)^{-1}$

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3. $\Gamma \equiv \Gamma(0^{-+} \to gg)$ in Mev.

4. $\sigma_{\gamma,cut} \equiv \sigma(pp \to 0^{-+} \to \gamma\gamma||\eta_\gamma| \leq 2.5, |p_{tr,\gamma}| \geq 25 Gev)$ in $fb \cdot 10^{-1}$ for $e_Q = -\frac{1}{3}$.

5. $\sigma_{Back} \equiv d\sigma_{Back}(|\eta_\gamma| \leq 2.5, |p_{tr,\gamma}| \geq 25 Gev)/dm_{\gamma\gamma} \cdot 10^{-2} M_{0^{-+}}$ in fb.

6. $L_1 \equiv k \cdot \frac{N_S}{\sqrt{N_{Back}}}$, $N_S \equiv \sigma_{\gamma,cut} \cdot L$, $N_{Back} \equiv \sigma_{Back} \cdot L$, $L = 10^5 \cdot pb^{-1}$, $k = 0.64$, $e_Q = -\frac{1}{3}$.

7. $L_2 \equiv \frac{N_S}{\sqrt{N_{Back}}}$, $N_S \equiv 16k \cdot \sigma_{\gamma,cut} \cdot L$, $N_{BacK} \equiv \sigma_{Back} \cdot L$, $L = 10^5 \cdot pb^{-1}$, $k = 0.64$, $e_Q = \frac{2}{3}$

8. M_Q is the mass of the singlet quark Q.

M_Q(Gev)	σ	σ_{cut}	Γ	$\sigma_{\gamma,cut}$	σ_{Back}	L_1	L_2
100	22.4	16.6	1.8	75	64	6.0	96
125	7.3	5.6	2.0	29	35	3.2	50
150	3.9	3.1	2.1	18	21	2.6	41
175	1.9	1.6	2.3	10.7	12	2.0	31
200	1.0	0.83	2.3	5.7	8.4	1.3	20
225	0.40	0.34	2.4	2.7	6.3	0.69	12
250	0.31	0.27	2.5	2.2	4.4	0.67	11
275	0.19	0.17	2.6	1.4	3.4	0.50	8.0
300	0.12	0.11	2.7	0.98	2.5	0.39	6.3
350	0.053	0.047	2.8	0.46	1.5	0.25	3.9
400	0.026	0.023	3	0.25	0.96	0.16	2.6

Table 2. The cross sections and branchings for the process $pp \rightarrow 1^{--} + ... \rightarrow \mu^+\mu^- + ...$

Here:

1. $\sigma_{cut,1} \equiv \sigma(pp \rightarrow 1^{--} + ... \rightarrow \mu^+\mu^- + ...||\eta_\mu| \le 2.5, |p_{tr,\mu}| \ge 5Gev)$ in fb for $Q = -\frac{1}{3}$.

2. $\sigma_{cut,2} \equiv \sigma(pp \rightarrow 1^{--} + ... \rightarrow \mu^+\mu^- + ...||\eta_\mu| \le 2.5, |p_{tr,\mu}| \ge 5Gev$ in fb for $e_Q = \frac{2}{3}$.

3. $\sigma_{Back} \equiv d\sigma_{DY}(pp \rightarrow \mu^+\mu^- + ...||\eta_\mu| \le 2.5, |p_{tr,\mu}| \ge 5Gev)/dm_{\mu\mu} \cdot M_{1^{--}} \cdot (2 \cdot 10^{-2})$.

4. $L_1 \equiv \frac{N_S}{\sqrt{N_{Back}}}$, $N_S \equiv \sigma_{cut,1} \cdot L$, $N_{Back} \equiv \sigma_{Back} \cdot L$, $L = 10^5 pb^{-1}$, $e_Q = -\frac{1}{3}$.

5. $L_2 \equiv \frac{N_S}{\sqrt{N_{Back}}}$, $N_S \equiv \sigma_{cut,2} \cdot L$, $N_{Back} \equiv \sigma_{Back} \cdot L$, $L = 10^5 pb^{-1}$, $e_Q = \frac{2}{3}$.

6. M_Q is the mass of singlet quark Q.

M_Q(Gev)	$\sigma_{cut,1}$	$\sigma_{cut,2}$	σ_{Back}	L_1	L_2
100	48	80	176	36	60
125	17	29	78	19	33
150	10	17	44	15	26
175	5.1	8.5	26	10	17
200	2.8	4.6	17	6.8	11
225	1.1	1.9	12	3.1	5.4
250	0.91	1.5	8	2.8	5.1

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